Global coverage from ad-hoc constellations in rideshare orbits

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ABSTRACT

A promising area of small satellite development is in providing higher temporal resolution than larger satellites. Traditional constellations have required specific orbits and dedicated launch vehicles. In this paper we discuss an alternative architecture in which the individual elements of the constellation are launched as rideshare opportunities. We compare the coverage of such an *ad-hoc constellation* with more traditional constellations. Coverage analysis is based on actual historical data from rideshare opportunities. Our analysis includes ground coverage and temporal revisits for Polar, Tropics, Temperate, and Global regions, comparing *ad-hoc* and Walker constellation.

INTRODUCTION

High temporal revisits are particularly useful for Earth science, reconnaissance, and weather applications. A constellation of satellites can provide significantly improved temporal coverage as compared to the temporal coverage from a single satellite. Due to their low per-unit cost and potential for ease of batch manufacturing small satellites are particularly well suited if revisit and coverage are favored over measurement quality.

Ad-hoc constellations

Most small satellites are launched as secondary payloads, so to build a constellation made up of secondary payload satellites, one must understand the coverage and revisit of such an *ad-hoc* constellation.

In a typical constellation each satellite is placed in a node as a part of an optimized system of orbits. Such a well-optimized system is not achievable with secondary launches without significant (or infeasible) onboard propulsion capability.

In this paper we explore and compare the ground coverage from satellites in ad-hoc orbits and satellites in Walker orbits. The expectation is that the Walker orbit constellation would provide superior performance, and is provided as a reference optimized constellation.

METHODOLOGY

To analyze the performance of the Ad-hoc constellation we use actual orbit data from the last 10 years of all known secondary payloads [1,2,3]. From this library dataset of satellite orbits we select a randomized set to represent the nodes in possible constellations that could have been built using historical launches. A Monte Carlo analysis [4] was performed to examine the option space of coverage and revisits [5] given the number of satellites and sensor Field of Views (FOV).

Data-set Compilation

All satellites with a launch mass of less than 350 kg were included in the data-set of *ad-hoc* launch opportunities. This metric was used to select the missions of opportunity because secondary payloads are generally <350 kg and few primary payloads are <350 kg. 309 satellites were identified in this way. Figures 1 and 2 show the characteristics of this satellite dataset.

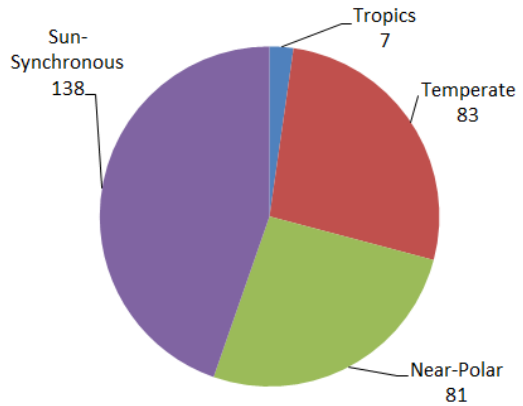

Figure 1: Polar vs Temperate vs Tropical vs Sun-Synchronous Orbit Breakdown. Defined using inclination of orbit.

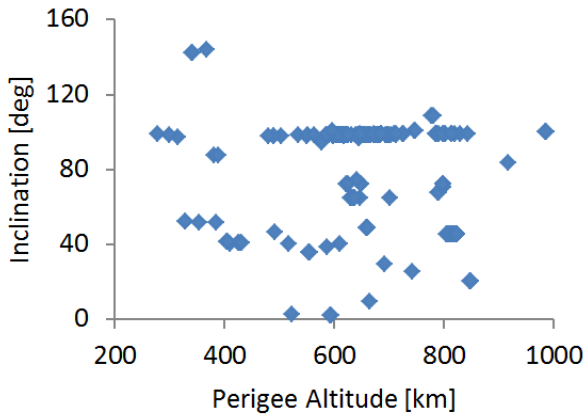

Figure 2: Perigee vs Inclination showing Ad-hoc missions of opportunity since 2001

Any orbit with apogee or perigee greater than 1600km were not included in the data-set since these orbits are not relevant to the applications targeted by this paper.

The data set is broadly considered as covering the Tropics, Temperate, Polar, and Global regions as defined in Table 1.

Table 1: Definitions of regions used in this paper, defined by latitude.

Region	Latitude Range [°]
Poles	> 66.5 and < -66.5
Temperate	-66.5 to -23.5 and 23.5 to 66.5
Tropics	-23.5 to 23.5
Global	-90 to 90

Monte Carlo method

The multivariate trade space is shown in Table 2. Altitude, eccentricity, FOV, Right Ascension of the Ascending Node or RAAN, Number of satellites in a constellation, and which specific satellites are in a constellation, are used as parameters for each Monte Carlo simulation run. Out of the 309 satellites in the database, "N" random satellites were picked for each of the 50 Monte Carlo runs for each value of N. For each Monte Carlo run, figures of merit (revisit time and % global coverage) were calculated for each FOV. The pseudo-code below describes the method:

For Monte_Carlo_Run = 1 to 50

For N = 2 to 12

Pick N random satellites from the Ad-Hoc Database of 309 Historical Missions

For FOV = 1.8, 7.9, 25.9, 41.9

Calculate figures of merit using the randomly selected satellites with sensors defined by FOV

End

End

End

Table 2: Parameters used to build each constellation.

Parameter	Value(s)
"N" – The # of satellites in a constellation	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
FOV (degrees)	1.8, 7.9, 25.9, 41.8
RAAN	Randomly generated
Perigee, Apogee, Inclination	Taken from the "N" randomly selected members of the database of "ad-hoc" missions of opportunity
Mean Anomaly	Arbitrarily set to 0
Argument of Perigee	Arbitrarily set to 0

Assumptions of orbit design and coverage analysis

The four selected FOVs (1.8°, 7.9°, 25.9°, 41.8°) are selected corresponding to swaths of 20, 90, 300, 500 km from a 650 km altitude. These FOVs are all nadir pointing. They are selected to represent a spread of typical swaths for pushbroom sensors. Swaths as large as MODIS (~1500km) are not included

because that class of instrument is more likely to have a dedicated platform. Swaths smaller than 20 km were not included because they are too small to analyze globally with STK v9.

Since RAAN values were not described in the data sources, random values were assigned for each satellite in the constellation at analysis time = 0, which is a fairer representation of a real ad-hoc constellation than picking an arbitrary value. The random assignment of RAAN values results in a more optimistic coverage results on our simulations. Since sun-synchronous orbits (consisting of almost half of the satellites in the database) have well defined RAAN values the coverage for actual ad-hoc orbits will be grouped, resulting in higher temporal coverage over particular regions at a particular time but poorer performance over the entire globe.

Mean Anomaly and Argument of Perigee were also unavailable so they were set to equal zero at analysis time = 0 because they do not critically influence the figures of merit.

Figures of merit – 75% coverage and mean revisit

Two Figures of Merit (FOM) are used: Mean revisit time and Time to 75% coverage. Each figure of merit is calculated over a grid of points, the "coverage grid," for all latitudes for a ten day analysis period.

Mean revisit time is defined as the mean gap in coverage. Put another way, as a constellation of satellites flies around the earth, a particular point is seen once, then again at some later time, then again at some later time and so on. The time between each of these observations is recorded and the mean is calculated for all points on the coverage grid.

Time to 75% coverage is the time that it takes from the start of the analysis to when the satellites have observed 75% of the coverage grid's surface area.

Definitions of "Poles," "Tropics", and "Temperate" follow standard definition and are shown in table 1.

RESULTS ANALYSIS

Choice of Statistical confidence

After running 50 Monte Carlo runs, a clear trend in the distribution of FOM values was observed. (Figure 3) The 1-sigma number is reported in the results below. This means 1 sigma (68 percent) of the random constellations generated as part of the Monte Carlo had values below this number, and only 32% had values above this number. The results for all the Monte Carlo runs for the case defined by 8 satellites and a 25.9 degree FOV, are shown as a histogram in Figure 4. Note the 68th percentile value is at 0.5 day revisit.

Figure 5 shows the results of the analysis for the coverage FOM. Figure 6 shows the results of the revisit FOM.

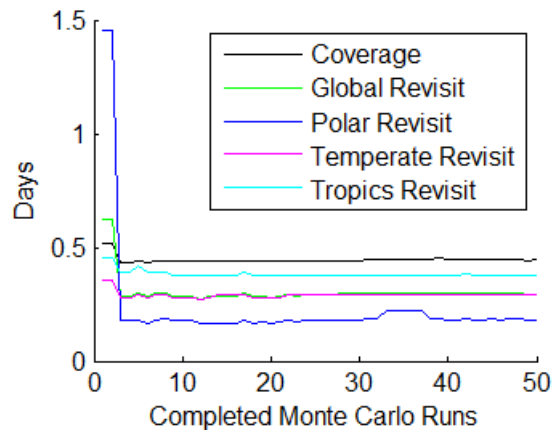

Figure 3: For FOV of 25.9 degrees and an eight-satellite constellation, this plot shows that 50 Monte Carlo runs were sufficient since the analysis has converged to a solution. Similar trends were observed for each of the combinations of FOV and N.

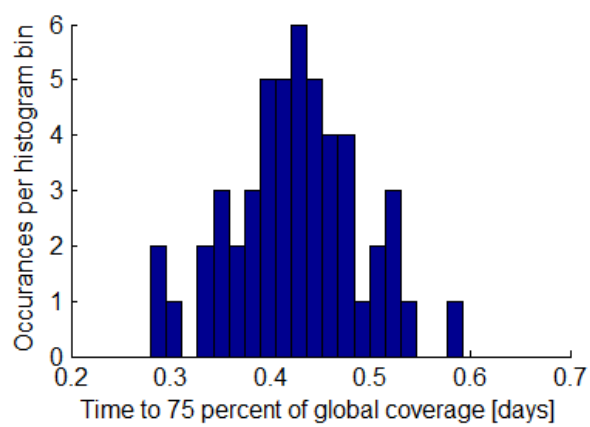

Figure 4: For FOV 25.9° and 8 satellite constellation. This histogram shows the distribution of coverage FOM for all 50 Monte Carlo runs. Note that the 68th percentile value is at 0.5 day revisit, consistent with the value in Figure 5

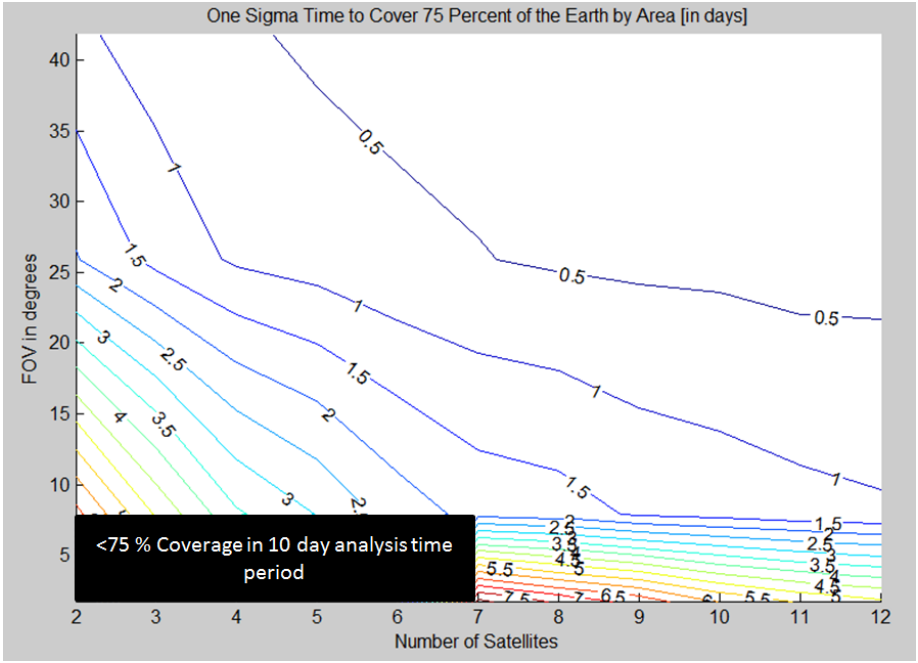

Figure 5: 1 sigma time of ground coverage for 75% of the Earth's surface as a function of instrument FOV and number of satellites in a randomly selected ad-hoc constellation. The 1 sigma value is chosen from the results obtained over 50 Monte Carlo runs performed using the parameters in Table 2

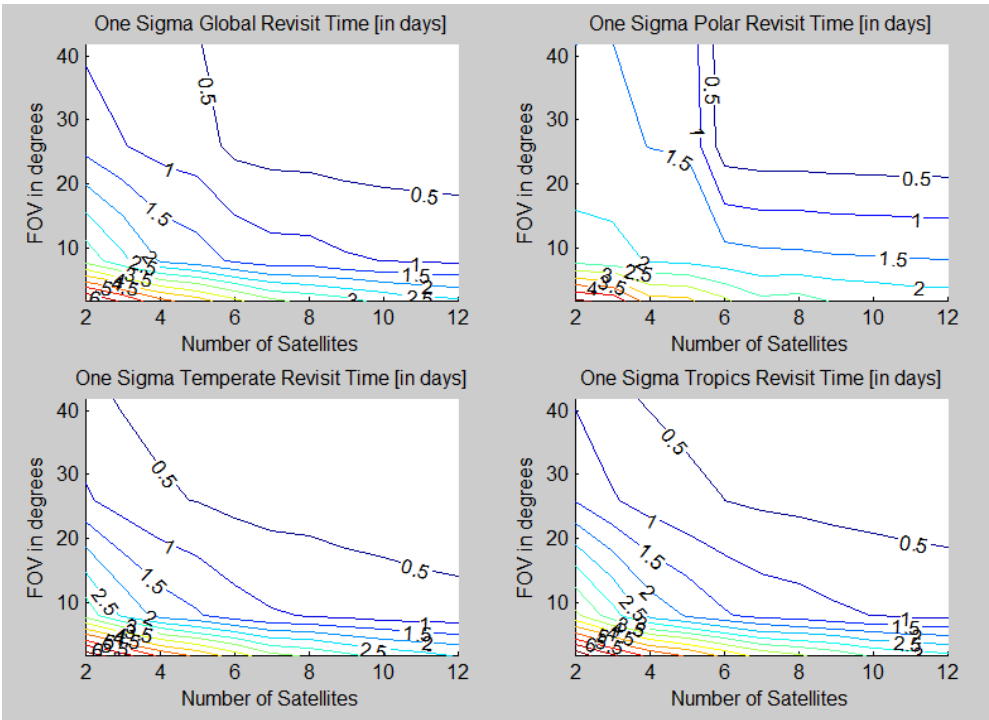

Figure 6: 1 sigma time between ground revisit in number of days as a function of instrument FOV and number of satellites in a randomly selected ad-hoc constellation. The 1 sigma value is chosen from the results obtained over 50 Monte Carlo runs performed using the parameters in Table 2. The results are divided in to 4 geographic regions: Global, Polar, Temperate, and Tropics. Definitions for these regions can be found in Table 1.

Definition of an optimized constellation

The planned constellation used for comparison is a "Walker Delta" constellation as designed by J. G. Walker [6]. The Walker constellations used for comparison were defined at 781 km altitude at an inclination of 86.4 degrees (the altitude and inclination of the Iridium constellation) for the same four FOVs and same number of satellites as the ad-hoc analysis (from 2 to 12). A walker constellation has multiple orbit planes of the same inclination but rotated about the pole (different RAAN). Each plane can have multiple satellites. Table 3 summarizes the particular Walker constellations that were used.

Since specific constellations were picked for each "N", multiple Monte Carlo runs were not required. The coverage and revisit plots for the Walker constellations are shown in Figures 7 and 8.

Table 3: Walker Constellation parameters used in analysis

Number of Satellites – "N"	Number of Satellites per Orbit	Number of Orbit Planes	RAAN between orbit planes [°]
2	1	2	90
3	1	3	120
4	1	4	45
5	2 (3 for one orbit)	2	90
6	2	3	120
7	2 (3 for one orbit)	3	120
8	2	4	45
9	3	3	120
10	2	5	72
11	1	11	32
12	3	4	45

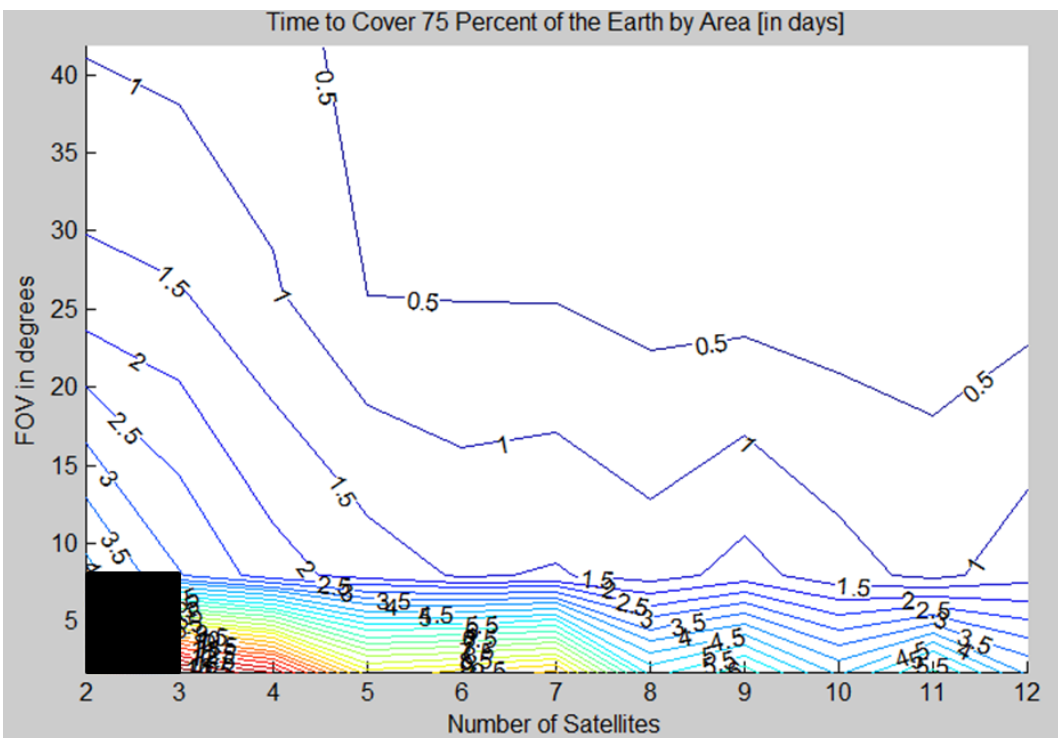

Figure 7: Time of ground coverage for 75% of the Earth's surface as a function of instrument FOV and number of satellites in a Walker constellation. The parameters of the Walker constellation are shown in Table 3. The black region did not achieve 75% coverage within the 10 day analysis period.

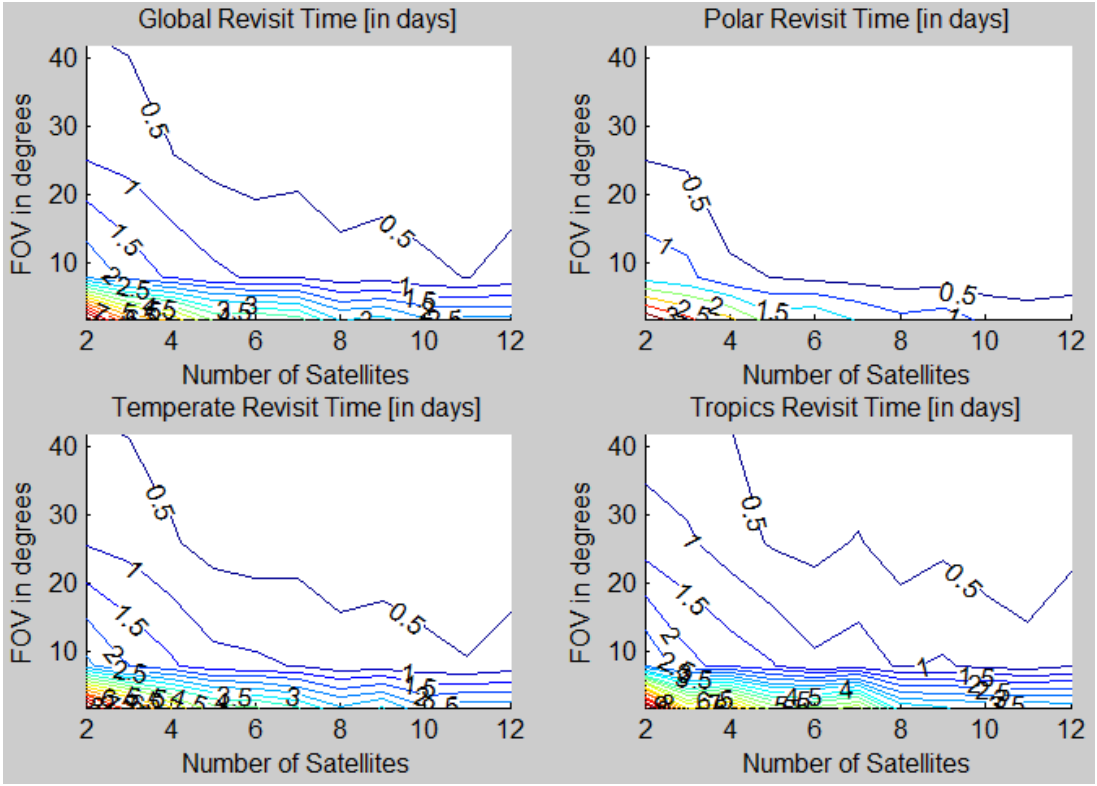

Figure 8: Mean time between ground revisit in number of days as a function of instrument FOV and number of satellites in a Walker constellation. The results are divided in to 4 geographic regions: Global, Polar, Temperate, and Tropics. Definitions for these regions can be found in Table 1. The parameters of the Walker constellation are shown in Table 3.

CONCLUSIONS:

Ad-hoc constellations can provide similar coverage to the more common constellation designs. Simulations have shown that ad-hoc constellations perform best for tropic and temperate revisit compared to the Walker constellation.

The Walker constellations considered had faster revisit times compared to the Ad-hoc constellations for Polar and Global regions. This is due to the orbits in the particular Walker constellation analyzed being near-polar, whereas only a subset of the ad-hoc constellation orbits are polar or near-polar.

The implications of the findings presented in this paper are applicable to future constellation design. For example lower latitude observations are underserved by polar satellites and can be augmented by using lower cost/smaller missions in an ad-hoc fashion. Under sampling can be remedied using smaller satellites capable of providing diurnal samples.

Acknowledgments

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